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HYPERFINE BEAMSTEERING USING A SIGNAL CROSSCORRELATION TECHNIQUE

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HYPERFINE BEAMSTEERING USING A
SIGNAL CROSSCORRELATION TECHNIQUE

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ABSTRACT

A method is developed to eliminate automatically the loss in signal amplitude of LASA phased sums with travel-time anomaly corrections due to small mis-alignments in the signal arrivals. This method is a hyper-fine or vernier adjustment of the trace alignments, making use of a least-squares estimate of the misalignments made from the time lags of all possible crosscorrelations between the signals. A mathematical description of the procedure and its errors is given. Three events with different signal-to-noise ratios recorded by 11 LASA subarrays were chosen as examples of the method. The results show improvements ranging from 0.0 to 0.5 db in the phased sum of the subarray sums. The results seem to depend on the signal-to-noise ratio of the event, the method performing best when that ratio is high.

INTRODUCTION

By beamsteering we mean shifting different array channels in time and forming a sum. The beam output is frequently also referred to as the "phased sum" or "delay-and-sum output" (Chiburis and Hartenberger, 1966). The interchannel time shifts consist of two parts:

1. Shifts calculated from an assumed signal propagation velocity across the array and an assumed direction of signal arrival.

2. Shifts which are intended to compensate for variation in transmission path phase characteristics between elements of the array, i.e., travel time anomalies. For LASA, these time adjustments have been observed to depend on the signal azimuth and phase velocity, that is, on the signal source region (Chiburis, 1966).

In beamsteering the LASA subarrays, only signal velocity is used; the intra-subarray travel time anomalies are negligible. However, when beaming subarray beams the travel time anomalies are significant: reduction in signal loss of approximately 5 db has been observed when the travel time anomalies are applied (Chiburis, 1966).

However, signal loss of approximately 1 db have been observed in beaming LASA subarrays (Chiburis and Hartenberger, 1966), and another 2-3 db of signal loss occurs when beaming the subarray beams. There appear to be two major contributing factors to the latter signal loss:

1. Variation in signal waveform across LASA;
2. Small errors in the travel time anomalies applied.

In this report we describe a method which should reduce signal losses due to the second of these causes. This method can be fully automated, provided that the signal arrival time is known and the signal/noise ratio is not too small - further work will be required to establish the threshold.

The first step is to measure the differences in signal arrival time which remain in the subarray beams after they have been time-shifted by both signal velocity and azimuth and the travel-time anomalies. Given the signal arrival time and knowledge of the signal duration based on prior experience, two methods for computing the signal arrival time differences suggest themselves:

1. Choose one of the N subarray beams as a reference channel. Compute the N-1 crosscorrelations of the other subarray beams with the reference channel, using a properly chosen time window around the signal arrival time (at this point the necessity for already having the signals almost lined up is apparent). Measure the lag at which each of these N-1 crosscorrelations peak. Assume that these lags give the inter-channel time shifts remaining to be applied.

2. Compute the entire correlation matrix of the N subarray beams, using a properly chosen time window around the signal arrival time. Measure the lag at which each of the $\frac{1}{2}N(n-1)$ crosscorrelations peak. Assume that these represent differences between inter-channel time shifts remaining to be applied. There are thus $\frac{1}{2}N(N-1)$ observations from which we can determine the N time shifts by least squares, having $\frac{1}{2}N(N-3)$ degrees of freedom (which is a lot). Estimate the standard error of each time shift, and do not apply any time shift which is not significantly different from zero. This should avoid the danger of nonsense results when the signal/noise ratio is small; see the discussion below.

The second method is obviously better than the first since it uses all possible correlations instead of just N of them. Also, the first method can be expected to fail if the reference channel happens to have a small signal or a signal waveform profoundly different from the others (significant variations in waveform have been observed; see, e.g., Flinn et al., 1966).

The only apparent relative drawback to the second method is computing time; but the difference in computing time between the first and the second method is actually quite small. Consider 21 subarray beams and a time window 150 points long. Then the first method requires the computation of twenty lags of each of twenty 150-point correlations, which requires a small fraction of a second on the CDC 1604-B. The second method requires the computation of 231 correlation functions (our library routine calculates the auto-correlations as well as the crosscorrelations), and the solution of 210 condition equations in 20 variables. Forming the correlation matrix should require approximately three seconds. It turns out that the solution of the least-squares normal equations for the time shifts can be written down explicitly without any matrix multiplication or inversion. Thus the computing time is approximately three seconds, which is not excessive.

Notice that the problem is not quite complete as we have stated it so far: a constraint is necessary. We choose one channel as a reference channel and constrain its time shift to be zero; i.e., we compute all the shifts relative to a reference channel (we emphasize again that the accuracy of the least-squares computed shifts in no way depends on the reference channel's having a good signal, as does the first method).

We now describe the method our program uses to calculate the least-squares time shifts.

Denote the time shifts we wish to estimate as s_1, s_2, ..., s_N, we can without loss of generality let the reference channel be the first channel. What we actually measure from examination of the correlation matrix are a set of $\frac{1}{2}N(N-1)$ differences in the shifts; we denote the lag at which the correlation between channel j and channel k peaks as t_{jk}, so our condition equations are:

$$s_2 - s_1 = t_{21}$$

$$s_3 - s_1 = t_{31}$$

$$....$$

$$s_N - s_1 = t_{N1}$$

$$s_3 - s_2 = t_{32}$$

$$s_4 - s_2 = t_{42}$$

$$....$$

$$......$$

$$s_N - s_{N-1} = t_{N,N-1}$$

The constraint equation is:

$$s_1 = 0$$

Thus we can write our condition equations in matrix form

$$H\underset{\sim}{s} = \underset{\sim}{t}$$

As an example , the equations for N = 5 are:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \end{bmatrix} = \begin{bmatrix} 0 \\ t_{21} \\ t_{31} \\ t_{41} \\ t_{51} \\ t_{32} \\ t_{42} \\ t_{52} \\ t_{43} \\ t_{53} \\ t_{54} \end{bmatrix}$$

It is easy to see the general rule for constructing the condition matrix H and for forming the least-squares normal equations:

$$(H^T H)\ \underset{\sim}{s} = H^T \underset{\sim}{t}$$

whence the estimated shifts are:

$$\hat{\underset{\sim}{s}} = (H^T H)^{-1} H^T \underset{\sim}{t}$$

The N-by-N normal equation matrix can be written down immediately:

$$H^T H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & \cdots \\ 0 & N-1 & -1 & -1 & -1 & \cdots \\ 0 & -1 & N-1 & -1 & -1 & \cdots \\ 0 & -1 & -1 & N-1 & -1 & \cdots \\ 0 & -1 & -1 & -1 & N-1 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

and its inverse is:

$$(H^T H)^{-1} = \begin{bmatrix} N & 0 & 0 & 0 & 0 & \cdots \\ 0 & 2 & 1 & 1 & 1 & \cdots \\ 0 & 1 & 2 & 1 & 1 & \cdots \\ 0 & 1 & 1 & 2 & 1 & \cdots \\ 0 & 1 & 1 & 1 & 2 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

The sum of squares of residuals when s is substituted back into the normal equations is

$$Q = (H\underset{\sim}{\hat{s}} - \underset{\sim}{t})^T (H\underset{\sim}{\hat{s}} - \underset{\sim}{t}) = \underset{\sim}{t}^T \underset{\sim}{t} - \underset{\sim}{\hat{s}}^T H^T H \underset{\sim}{\hat{s}}$$

The standard deviation of the residuals is thus

$$\hat{\sigma}_r = \left[Q/(\tfrac{1}{2}N^2 - \tfrac{1}{2}N - N)\right]^{\frac{1}{2}} = \left[Q/(\tfrac{1}{2}N^2 - 3N/2)\right]^{\frac{1}{2}}$$

The standard deviation of the k'th estimate $\hat{s}_k$ is

$$\hat{\sigma}_k = \hat{\sigma}_R \left[S_{kk}\right]^{\frac{1}{2}}$$

where $S = (H^T H)^{-1}$, and S_{kk} is the k'th diagonal element of S (Anderson, 1958).

To test the hypothesis that an estimated shift is significantly different from zero, we form the ratio of the estimate to its standard deviation, i.e., we look at how many standard deviations away from zero the estimate is. This is a t-statistic,

and we can get the 90 percent confidence limits straight out of the tables (Anderson, 1958).

If we are talking about LASA subarrays, the appropriate range of N is, say, 10-21, for which the critical value of t at the 90 percent confidence level is:

N	$\frac{1}{2}N(N-3)$	t_{90}
10	35	2.72
14	77	2.65
18	135	2.62
20	170	2.61
21	189	2.60

Thus it is very slowly varying in this range. We will not go far wrong if we simply use a value 2.60 for all N in this range. That is, we agree to apply the time shifts which lie more than 2.6 standard deviations away from zero, and ignore those which fall closer to zero than 2.6 times the standard deviation.

This should have the effect of rejecting nonsense shifts when a low signal/noise ratio occurs. In addition, we can use our knowledge of the fact that the channels are already very nearly aligned, and reject shifts which are greater than some agreed amount, regardless of their standard deviation. As a trial value, we have taken this cutoff as 0.5 seconds.

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PROCEDURES

Three events with differing signal-to-noise ratios recorded at the Montana LASA were selected for this study. The pertinent information concerning them is summarized in Table 1. The measurements of the bandpass-filtered phased sum amplitudes, using travel time anomalies, are given in the first part of Table 2. Each trace represents the phased sum of 25 sensors from the indicated LASA subarray. As described in previous reports (see for example, Flinn, et al., 1966) these data were first detrended, corrected to true ground motion in millimicrons, and then bandpass filtered with the standard SDL bandpass filter. The notation in the figures is as follows: PPA stands for phased sum of the subarray phased sums with anomalies, and PPAV stands for phased sum of the subarray phased sums with anomalies vernier beamsteered. All the numerical measurements were obtained automatically by using SDL library programs MODLAS and TFOSAN.

RESULTS

The results of this study are presented in the second part of Table 2 and in Figures 1 through 6. Figure 1 shows the signals from the three events used for computing the cross-correlation matrix. All 5 seconds shown were used to compute cross-correlation functions sampled as often as the data (20 samples per second) and out to a maximum time lag of one second. Figures 2, 3, and 4 show the input and output traces for each case; that is, input to and output from the vernier beamsteering program. In these figures, it is possible to see slight time shifts that were detected and subsequently eliminated by the shifting process. Figures 5 and 6 are the sums before and after processing respectively. The second half of Table 2 lists the numerical results of the study.

The last entry in Table 2 is the standard deviation of the time shifts computed as described above. All of the estimated time shifts for the Nov. 4, 1965 event were within 2.6 standard deviations of zero and were therefore eliminated. The PPAV for this event is thus equal to the PPA. However, for the 20 Nov. 1965 and the 9 Dec. 1965 events, six and four time shifts respectively were larger than 2.6 standard deviations. Application of these shifts produces the differences in the input and output for these events. At no time did we have to eliminate a time shift that was greater than half a second.

The standard deviation itself is a good measure of how well the method works. The 4 Nov. 1965 event had the lowest signal-to-noise ratio on the PPA trace and the largest standard deviation. The large standard deviation occurs both because of the dissimilarity between the signals from this event and the larger proportionate noise level. On the other hand, the 9 Dec. 1965 event had the highest signal-to-noise ratio and the lowest standard deviation but did not exhibit the largest gain from the vernier beamsteering procedure. It appears that the anomalies for this event were more accurate than those for the Nov. 20, 1965 event. This is supported by the lower number of non-zero shifts.

These results, though small (0.6 and 0.1 db respectively) are nevertheless considered significant. They are corrections to a refined and very accurate process, the phased summation of LASA data using travel time anomalies. Therefore we should expect them to be small. However what makes them important is that they result from eliminating one more cause of signal degredation in phased summation. If one half a db can be saved by vernier

beamsteering only 11 subarray outputs, perhaps a full db can be saved by processing all 21. We have demonstrated here a method which resulted (in one case) in reducing by one-half the signal loss actually observed (Chiburis and Hartenberger, 1966).

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Chiburis, E.F., and Hartenberger, R.A., 1967, Signal-to-Noise ratio improvement by beamforming LASA seismograms: SDL Report 173, Seismic Data Laboratory, Alexandria, Virginia.

Flinn, E.A., Hartenberger, R.A., and McCowan, D.W., 1966; Two examples of maximum likelihood filtering of LASA seismograms: SDL Report 148, Seismic Data Laboratory, Alexandria, Virginia.

TABLE 1

EVENT DATA

	Nov. 4, 1965	Nov.20, 1965	Dec. 9, 1965
Latitude	27.2S	15.4S	17.7S
Longitude	67.3W	174.SW	178.3W
Origin Time (GMT)	00:40:03.0	03:47:52.4	13:25:40.7
Depth (km)	131	12	650
Magnitude (m_b)	4.1	5.2	5.1
Region	Argentina	Tonga	Fiji Islands
Epicentral distance to A0	81.5°	86.9°	91.0°
Back Azimuth (degrees east of north)	145°	243°	245°
Horizontal velocity to A0 (km/sec)	20.9	22.5	23.3

TABLE 2

RESULTS

	Nov.4, 1965	Nov.20, 1965	Dec. 9, 1965
PPA Signal (mμ)	6.59	13.15	48.14
PPA Noise rms (mμ)	0.33	0.31	0.34
PPA S/N	19.69	42.61	141.94
PPAV Signal (mμ)	6.59	13.57	48.66
PPAV Noise rms (mμ)	0.33	0.30	0.34
PPAV S/N	19.69	45.76	143.74
Gain (db)	0.0	0.6	0.1
Standard deviation (sec)	.072	.049	.022

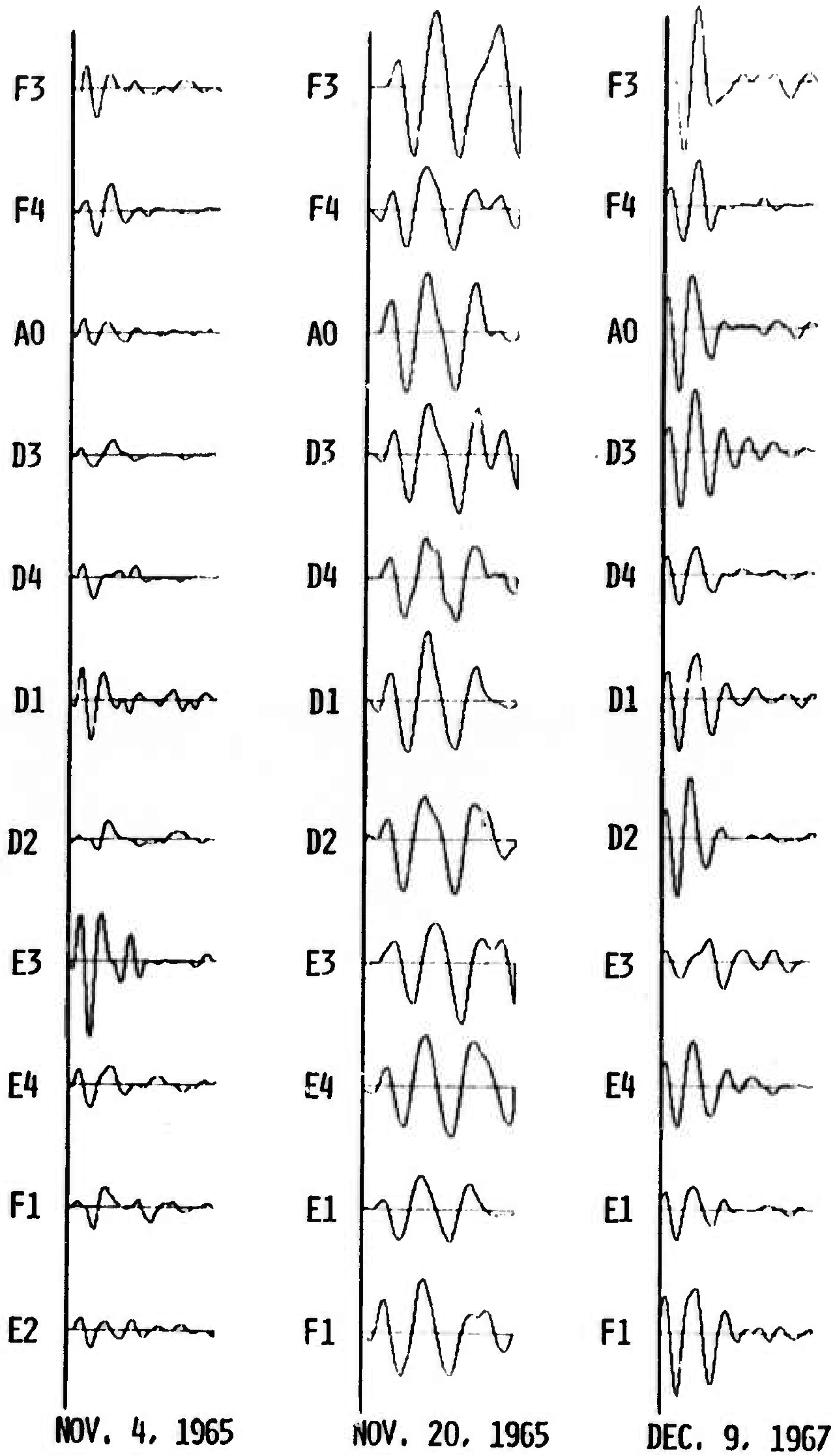

Figure 1 Signals used for computing the cross-correlation functions

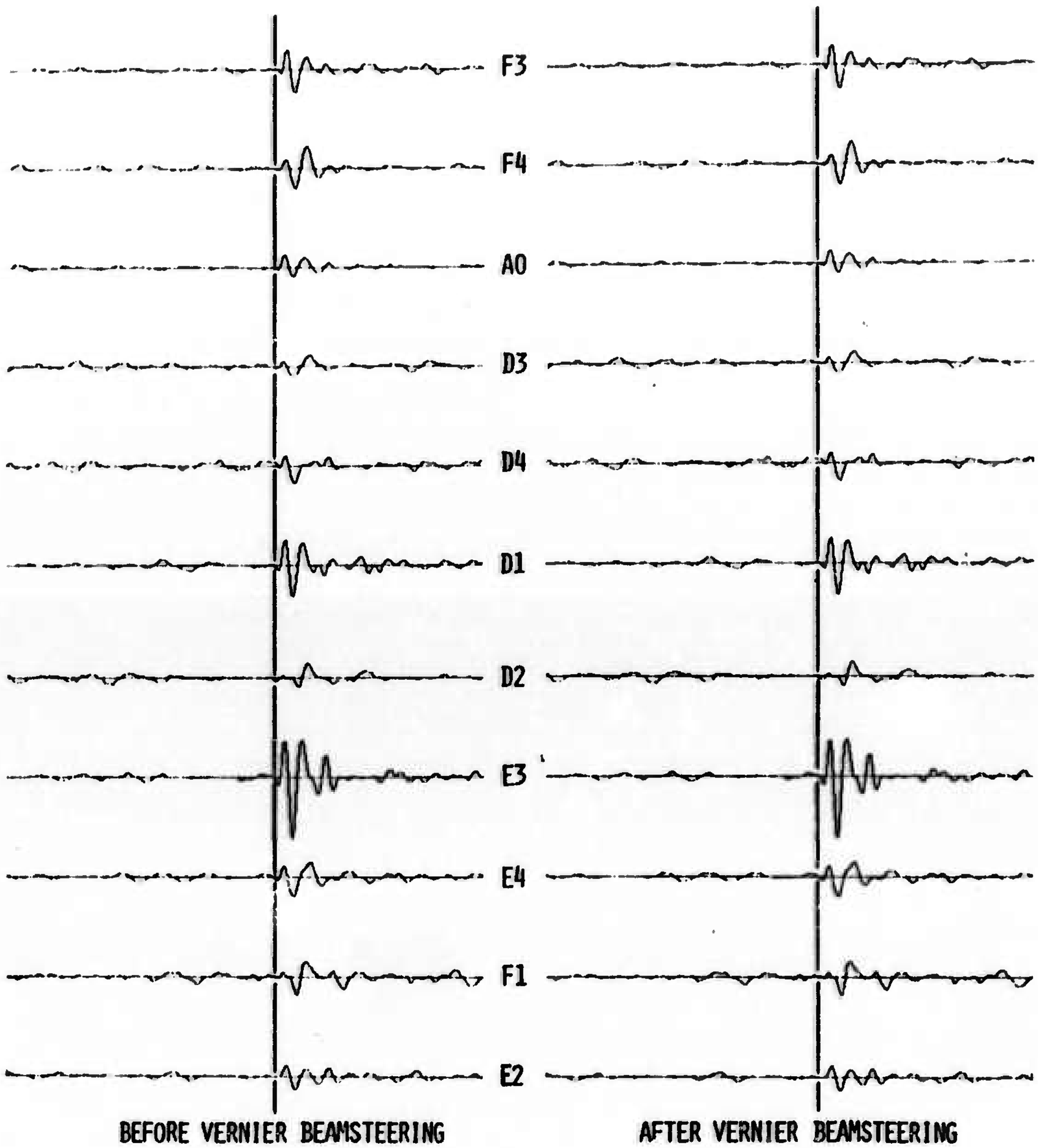

Figure 2 Nov. 4, 1965 event subarray sums

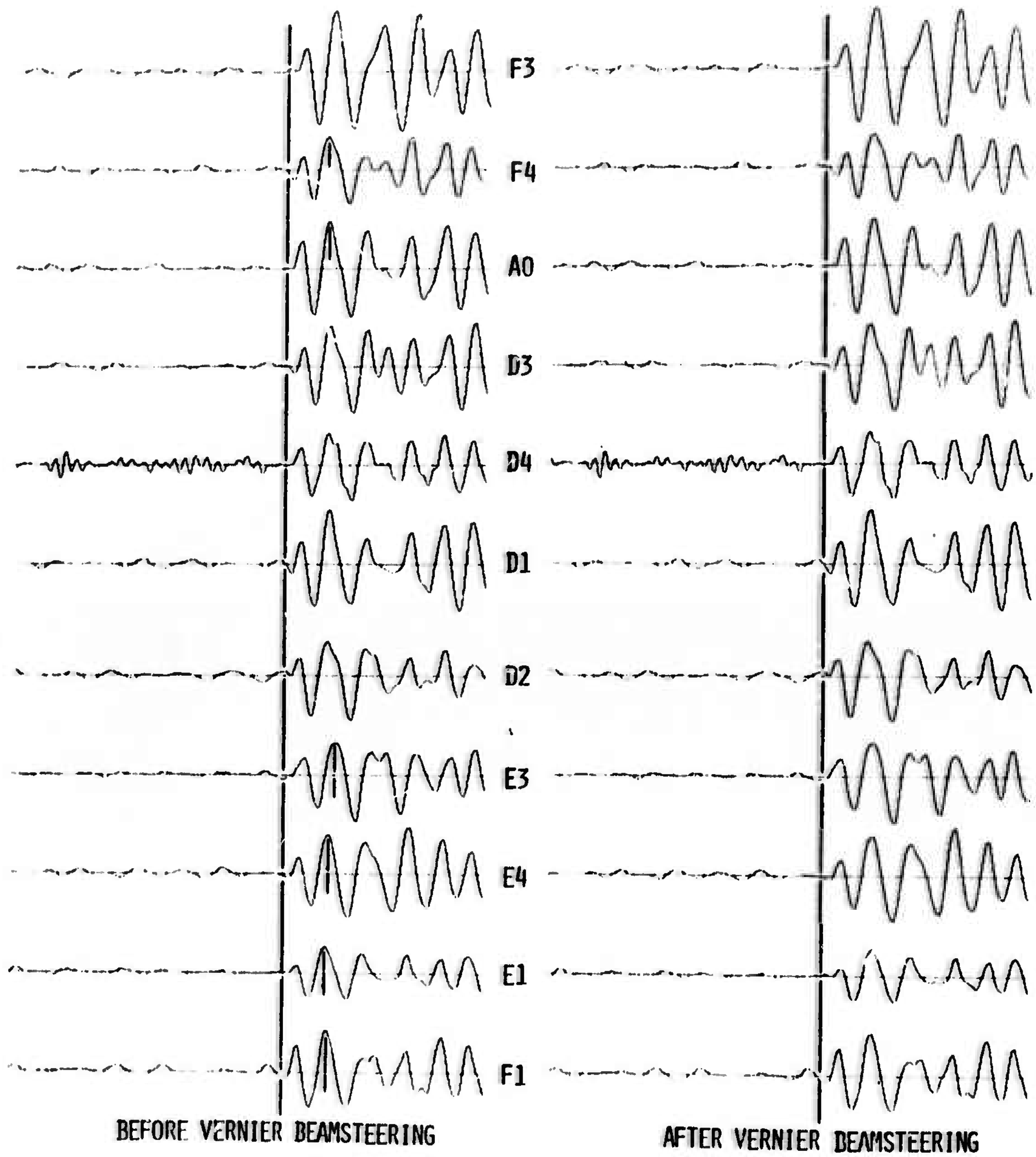

Figure 3   Nov. 20, 1965 event subarray sums

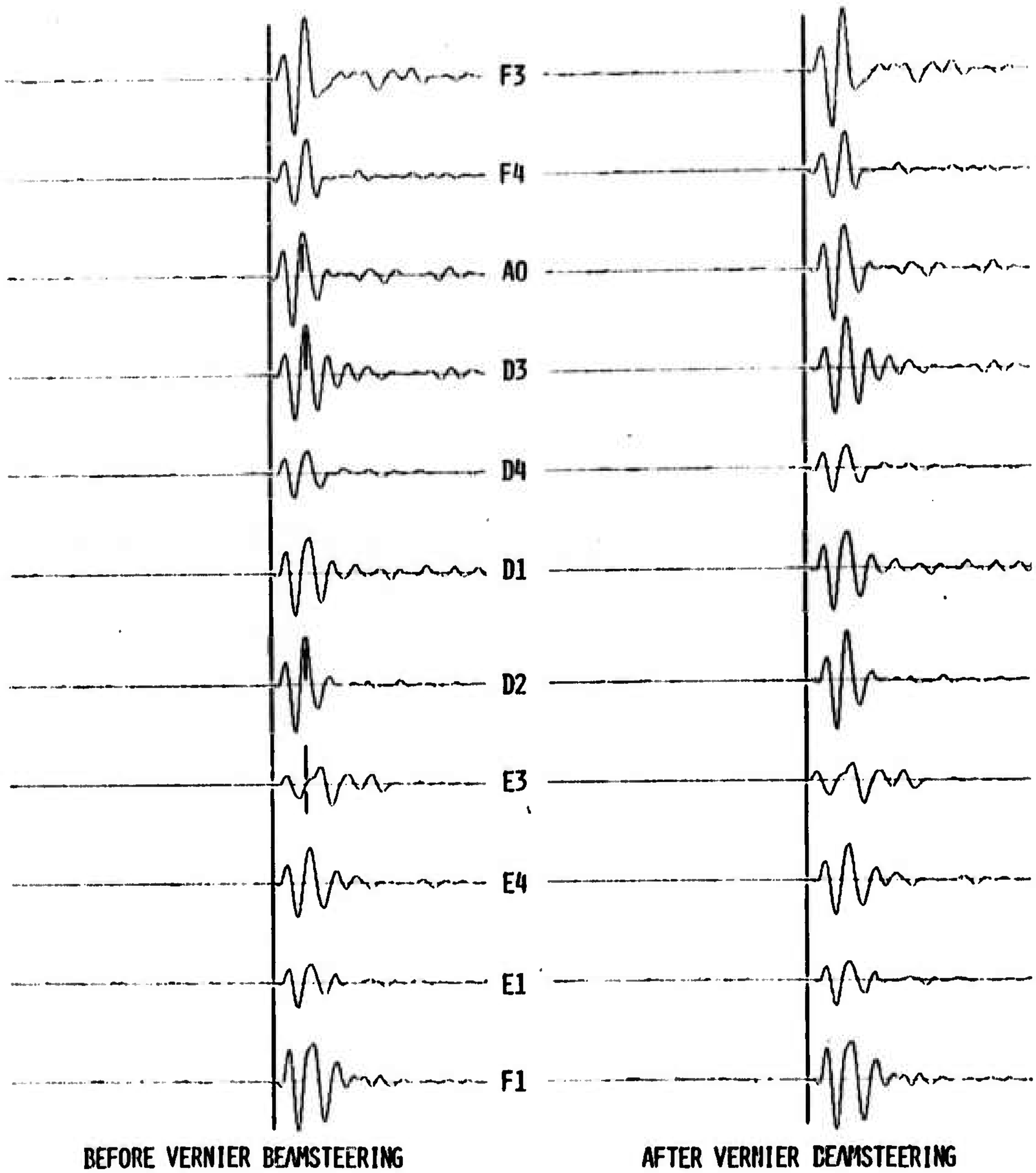

Figure 4 Dec. 9, 1965 event subarray sums

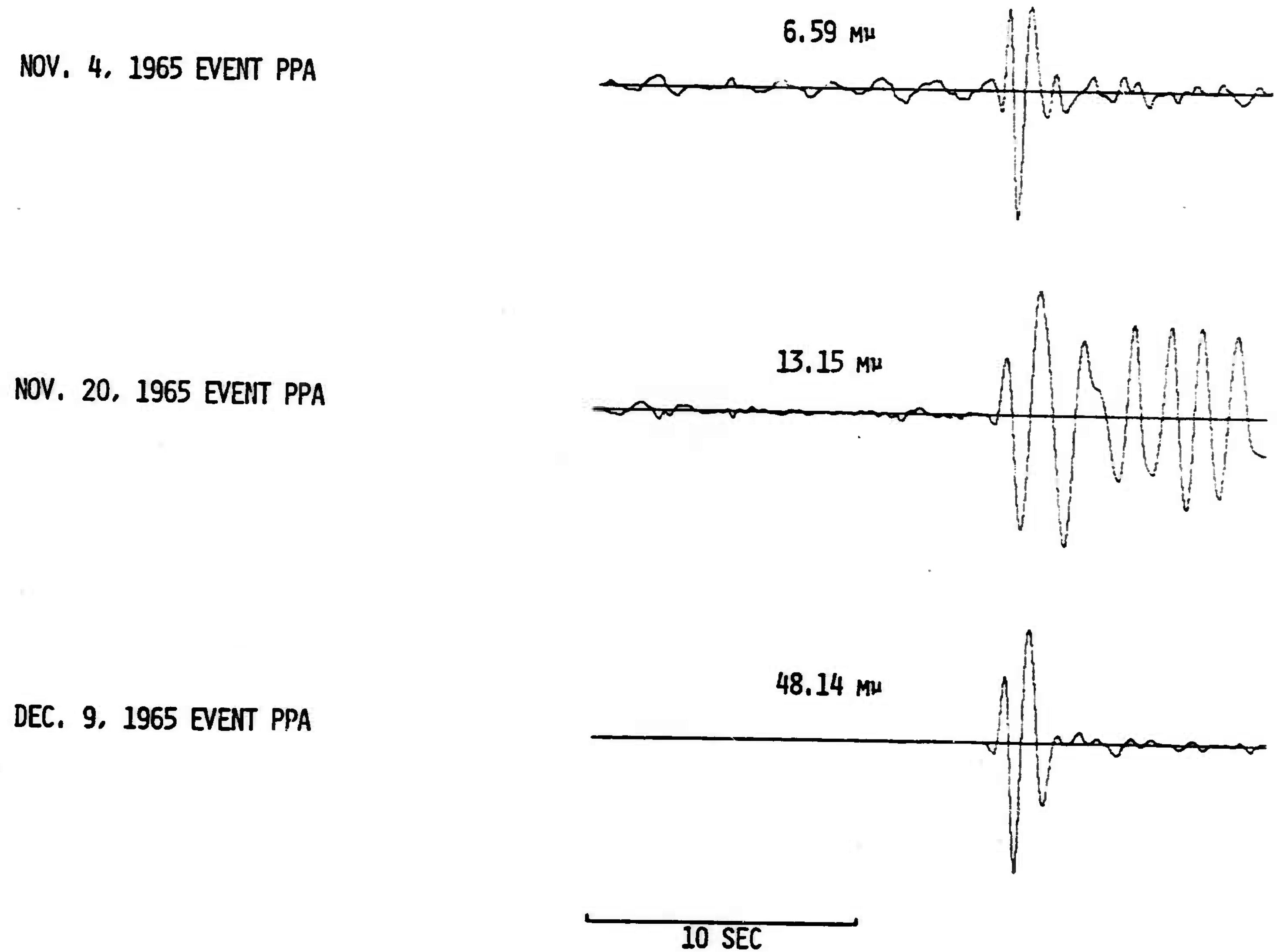

Figure 5 LASA phased sums before vernier beamsterring

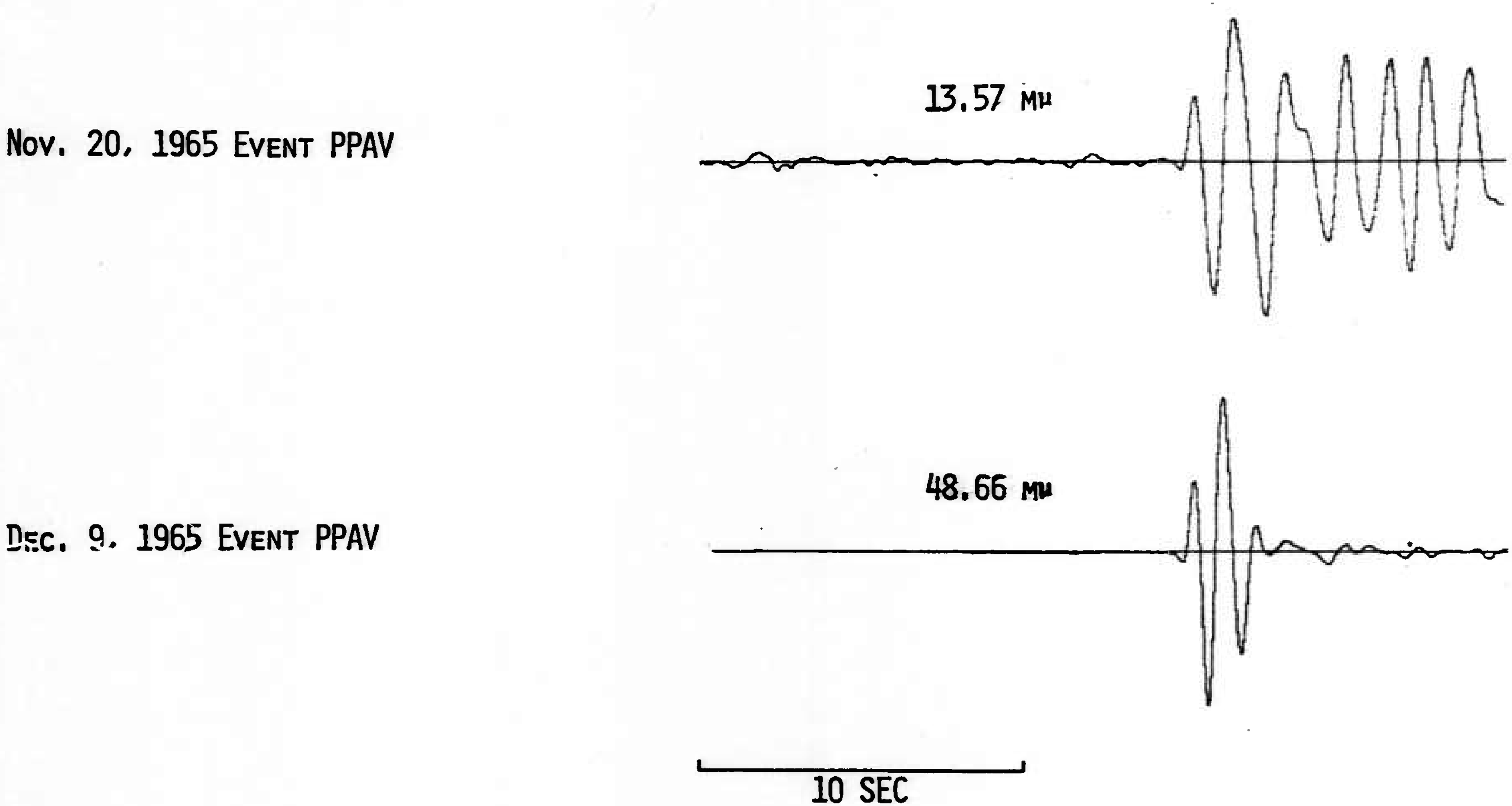

Figure 6 LASA phased sums after vernier beamsteering

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13. ABSTRACT
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14. KEY WORDS
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Cross-correlation analysis
Beamsteering of LASA data
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Digital processing of seismic data

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